Multi-service System: An Enabler of Flexible 5G Air-Interface

Lei Zhang, Ayesha Ijaz, Pei Xiao and Rahim Tafazolli

***Abstract*— Multi-service system is an enabler to flexibly support diverse communication requirements for the next generation wireless communications. In such a system, multiple types of services co-exist in one baseband system with each service having its optimal frame structure and low out of band emission (OoBE) waveforms operating on the service frequency band to reduce the inter-service-band-interference (ISvcBI). In this article, a framework for multi-service system is established and the challenges and possible solutions are studied. The multi-service system implementation in both time and frequency domain is discussed. Two representative subband filtered multicarrier (SFMC) waveforms: filtered orthogonal frequency division multiplexing (F-OFDM) and universal filtered multi-carrier (UFMC) are considered in this article. Specifically, the design methodology, criteria, orthogonality conditions and prospective application scenarios in the context of 5G are discussed. We consider both single-rate (SR) and multi-rate (MR) signal processing methods. Compared with the SR system, the MR system has significantly reduced computational complexity at the expense of performance loss due to inter-subband-interference (ISubBI) in MR systems. The ISvcBI and ISubBI in MR systems are investigated with proposed low-complexity interference cancelation algorithms to enable the multi-service operation in low interference level conditions.**

***Index Terms*—5G, multi-service, interference cancelation, multi-rate, F-OFDM, UFMC, SFMC, physical layer network slicing (PNS).**

I. Introduction

5TH Generation (5G) wireless communication systems are expected to address unprecedented challenges to cope with a high degree of heterogeneity in terms of services, device classes, deployment environments and mobility levels [1]. Different applications and uses cases specified by the 5G research community have been categorized into three main communication scenarios [2]: enhanced mobile broadband (eMBB), massive machine type communications (mMTC), ultra-reliable and low latency communications (URLLC).

Designing a separate standalone radio system for each service to support heterogeneous requirements is not a feasible solution, since the operation and management of the systems will be highly complex, expensive and spirally inefficient. On the other hand, it is cumbersome to design a unified all-in-one radio frame structure which meets the requirements for all types of services. For example, mMTC may require smaller subcarrier spacing (thus larger symbol duration) to support massive delay-tolerant devices. URLLC, on the other hand, has more stringent reliability and latency requirements, thus, symbol duration must be significantly reduced. The subcarrier spacing and symbol duration of eMBB communication are, however, constrained by doubly-dispersive channel (i.e., channel coherence time and coherence bandwidth). Therefore, there is a limit on subcarrier spacing and symbol duration in order to avoid performance bottlenecks due to channel impairments.

One viable solution to support diverse requirements in 5G is to multiplex the multiple types of services in one baseband system in orthogonal time and/or frequency resources, with either physical (e.g., using guard interval or guard band) or algorithmic (e.g., filtering or precoding the data) isolation to avoid the interference between them [3][4]. Frequency division multiplexing (FDM) is preferred in 3rd Generation Partnership Project (3GPP) for multiplexing different services due to several advantages such as good forward compatibility, ease of supporting services with different latency requirements, energy saving by turning off some transmit time intervals (TTIs) etc. Such a frequency division multiplexing multi-service system is shown in Fig. 1 (a), where an optimal frame structure has been designed for different types of services in different service frequency bands, with a low out of band emission (OoBE) subband filtering operation to reduce the interference. A guard band could be used between them, as an option, to further mitigate the interference.

In addition to economic benefits and dynamic resource allocation, multi-service approach exclusively optimizes the parameters to cater for the unique service requirements in each scenario. Moreover, the multi-service systems can enable loose time synchronization scheme and may save signaling overhead (e.g., time advance (TA) in Long Term Evolution (LTE)), since all service signals are well-separated in the frequency domain. The spectrum allocation flexibility of the multi-service system can also be combined with other techniques such as cognitive radio networks [5] [6] [7], where the fragmented spectrum can be dynamically occupied by various type of services and keep the services from significant inter-service-band-interference (ISvcBI).

It can be verified from mathematical analysis that combining different numerologies in one frequency band will destroy the orthogonality of multi-carrier systems, resulting in ISvcBI. Inserting guard band between service bands can mitigate the interference, however, at the cost of reduced radio spectrum efficiency. Waveforms with low OoBE are important in the multi-service system in order to isolate the signals between services and reduce the ISvcBI with/without limited guard band between them. Several new waveforms have been

The authors are with the 5G Innovation Centre (5GIC), Institute for Communication System, University of Surrey, Guildford, GU2 7XH, UK.

proposed for next generation communications with OoBE level as the most important key performance indicator (KPI). Among them, filtered orthogonal frequency division multiplexing (F-OFDM) [4] and universal filtered multi-carrier (UFMC) [3] [8] are particularly promising due to their excellent trade-off between complexity and performance. Thus, they have been investigated as the main candidate waveforms for 5G in the 3GPP RAN1 meeting [9].

The multi-service system may fundamentally change the air-interface architecture and algorithms employed in existing single service systems (e.g., OFDM based LTE). These changes and extensions may require rethink the availability and effectiveness of using existing design criteria, algorithms, optimization and performance analysis for multi-service systems. Specifically, the multi-service system is different in the following aspects:

- Even with low OoBE waveforms, the multi-service system is no longer orthogonal due to the trade-off between the performance and system overhead. The inter-symbol-interference (ISI) and ISvcBI exist in the system.
- Due to the subband filtering, the filter gain at different subcarriers in one subband may be different, resulting in uneven power allocation among subcarriers and, hence, performance loss [3].
- Multi-rate (MR) implementation may be essential to make the multi-service system complexity affordable [14]. However, compared with single-rate (SR) implementation, MR may degrade the system performance due to the inter-subband-interference (ISubBI) generated in up/down-sampling process.
- F-OFDM and UFMC are designed by maximizing the frequency and time localization property, respectively, resulting in the two waveforms favoring different application scenarios.

All of the aforementioned aspects will be systematically discussed in this article to provide guidelines for the 5G system design and solutions to the network slicing on physical layer resource multiplexing and isolation. Note that this article will focus on the fundamental limitations and applicable scenarios for the multi-service systems based on F-OFDM and UFMC waveforms. The original waveform signal model can be found in [4] [14]; while the mathematical model of a multi-service system and the details of algorithms used in the article can be found in [3] [14]. It must be noted that in a single-service system (such as LTE) with single numerology, inter-carrier-interference (ICI) defines the interference generated among the subcarriers. However, ICI is not sufficient to capture all the impairments incurred in a multi-service system, where different services may use different subcarrier spacing and symbol duration. The ICI definition, analysis and cancelation algorithms in the traditional single-service system cannot be applied to the multi-service system. To differentiate it, we define the *interference between service bands as ISvcBI* and the *interference between subbands in one service band as ISubBI*.

Note that [10] proposed a multi-service system called flexible configured OFDM (FC-OFDM) by using time domain windowing to reduce the system OoBE and a novel low-complex precoding (with 2 taps only) to mitigate the interference. However, it may result in a higher ISvcBI and a large guard band may be required to reduce interference level in edge subcarriers. In addition, [11] proposed a multi-service system based on the filter-bank multicarrier (FBMC) waveform that may provide a better OoBE and isolation between service bands. However, as also pointed out in literature [3] [4] [10] [12], FBMC system is significantly more complex than OFDM–based system. Nevertheless, the proposed interference cancelation schemes are generic and can be combined with other systems such as FC-OFDM and FBMC proposed in [10] and [11], respectively.

In this article, we build a framework for multi-service system and categorize the possible subband filtering implementations and synchronized systems in frequency and time domains. The roles of the waveform and subband filter in the multi-service system are discussed, and the two waveforms' limitations and viable subband bandwidth regions will be also discussed. The waveforms' prospective application scenarios in the context of 5G are investigated. We also discuss single-rate and multi-rate implementations of multi-service system. The system orthogonality and the sources of the ISvcBI and ISubBI will be discussed in detail. In addition, the ISvcBI and ISubBI cancelation algorithms and simulation results are presented.

In this article, we will use the following parameters for numerical evaluations unless otherwise specified.

- 20 MHz system bandwidth and 30.72 MHz sampling rate contains 2048 subcarriers.
- Zero padding (ZP) or cyclic prefix (CP) length is 160 samples.
- The respective filter for F-OFDM and UFMC is Windowed Sinc filter [4] and Chebyshev filter (with OoBE being -50 dB) [12] and the filter length is 1024 and 160 samples, respectively.
- We consider the international telecommunication union (ITU) defined urban micro (UMi) channel for all simulations.

II. Multi-service System Implementations

A. *Multi-service System Frequency Domain Implementation*

For a multi-service system, it is natural to assume that each service supports one or more users, where each user can be granted an arbitrary number of consecutive or non-consecutive physical resource blocks (PRBs). The possible bandwidth allocation and subband filtering methods in a multi-service system are shown in Fig. 1 (a). The conventional multi-carrier systems (e.g., LTE/LTE-A) have a 3-tier frequency resource structure, i.e., system bandwidth, PRB and subcarrier. However, the multi-service system has a 4-tier frequency resource structure, i.e. system bandwidth, service bandwidth, PRB and subcarrier. The level on which the subband filter operates will affect the multi-service system performance and implementation complexity. Fig. 1 (a-1), (a-2) and (a-3) show filtering applied to PRB, user and service, respectively.

Each subband filtering scheme has its own pros and cons. PRB is the minimum scheduling granularity and the subband filtering based on one or more PRBs (Fig. 1 (a-1)) has maximum design flexibility. On the other hand, this implementation also incurs the highest computational complexity due to the dense subband filtering operation. On the contrary, service based subband filtering method (Fig. 1 (a-3)) has the lowest computational complexity and the users (and PRBs) in one service share the same filter design parameters. Hence, the system loses the advantage of independently optimized filter design to cater for the specific scenarios. User-based subband filtering as shown in Fig. 1 (a-2) is a trade-off between PRB-based and service-based methods. Note that PRB-based implementation is the most general case.

Except the complexity and flexibility considerations, granularity of the subband also depends on the employed waveform. Waveforms with better frequency but worse time localization property (e.g., F-OFDM) may favor user or service based implementation. On the other hand, waveform with better time but worse frequency localization property (e.g., UFMC) may prefer the PRB based implementation. This will be discussed in the next in detail.

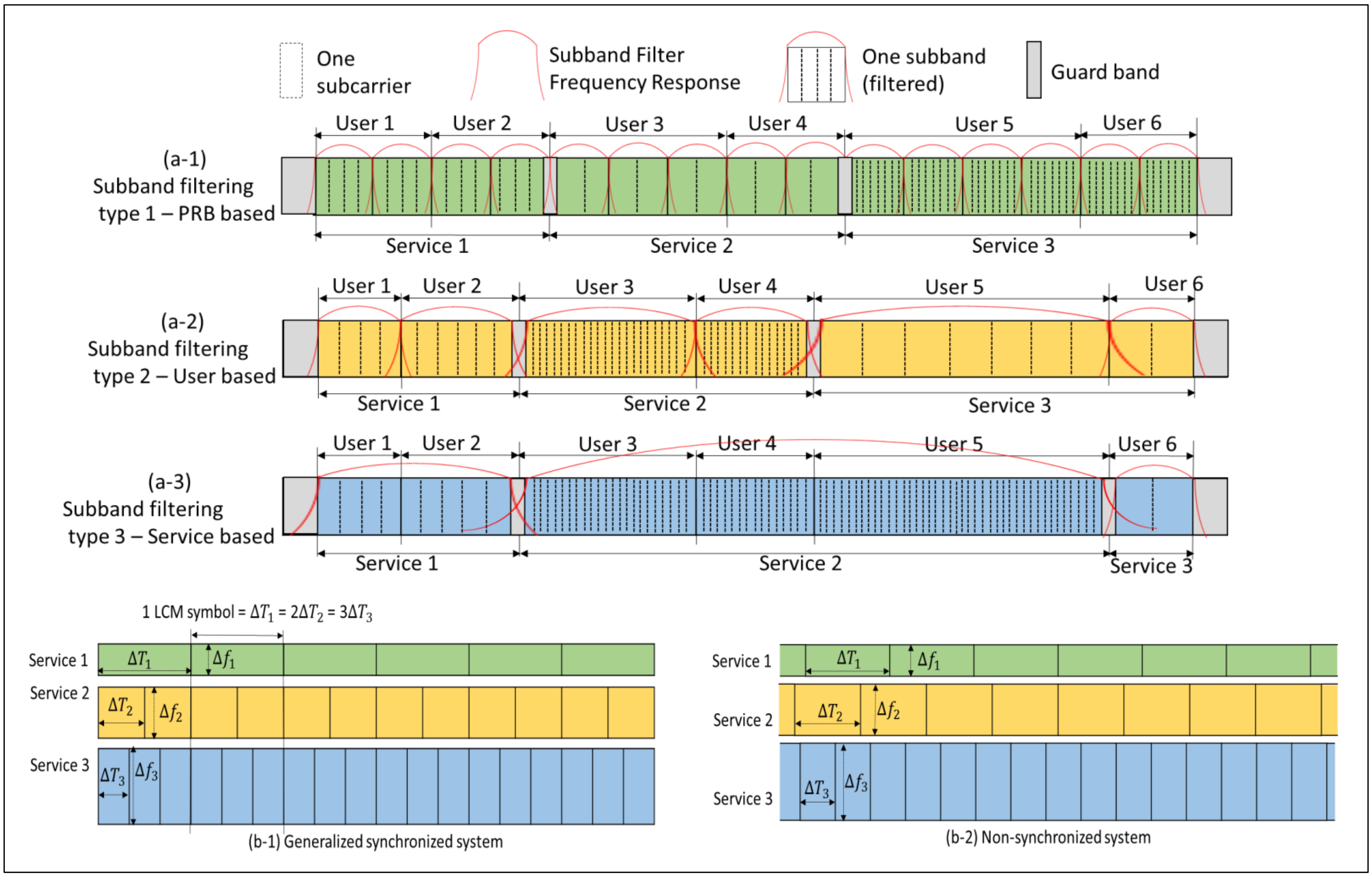

Fig. 1 Multi-service system frequency and time domain implementations. (a) Three types of subband filtering methods. (b) Generalized synchronized and non-synchronized multi-service systems

B. Multi-service System Time Domain Implementation

Since the symbol duration is different for different services, this makes the (spectrally efficient) synchronization of the whole system practically impossible. For example, in OFDM systems, without considering the guard interval, two services with subcarrier spacing $\Delta f_2 = 2\Delta f_1$ implies that the symbol duration has the relationship $\Delta T_1 = 2\Delta T_2$ (see Fig. 1 (b-1) as an example). Consequently, the symbols in service 2 cannot synchronize with symbols in service 1. However, we can take advantage of the fact that duration of every 2 symbols in service 2 is the same as symbol duration in service 1 and we call this a generalized synchronized (GS) system. In such a system, there is a duration, equivalent to the least common multiple (LCM) of symbol durations of all services. Fig. 1 (b-1) is an example of the GS system, which has the advantage of simplified system and algorithms design and performance analysis since only limited symbols need to be considered in a processing window and every LCM window has the same overall performance.

However, in a GS system, the symbol duration plus overhead (such as filter tails and guard interval, etc.) for all services should have a least common multiple, which might reduce the system design flexibility. Moreover, all services have to be synchronized to take the advantage of GS system. Therefore, a non-synchronized MS system as given in Fig. 1 (b-2) may be considered in some scenarios.

III. WAVEFORMS DESIGN AND COMPARISONS

A. F-OFDM and UFMC Design Criteria

According to Balian-Low Theorem [13], there is no way to utilize a well-localized prototype filter in both time and frequency, along with maintaining orthogonality and transmitting at the Nyquist rate. Hence, relaxing one condition guarantees the other two factors. UFMC and F-OFDM are two contrasting examples. The former uses short filter to secure good time localization property. In such a case, the ISI can be minimized but the scarificed filter frequency localization property may generate more ISvcBI/ISubBI in multi-service systems. While the F-OFDM uses long filter with sharp cut-off resulting in the ISvcBI/ISubBI minimization, this may generate ISI which could be significant in some scenarios such as narrow band mMTC communications.

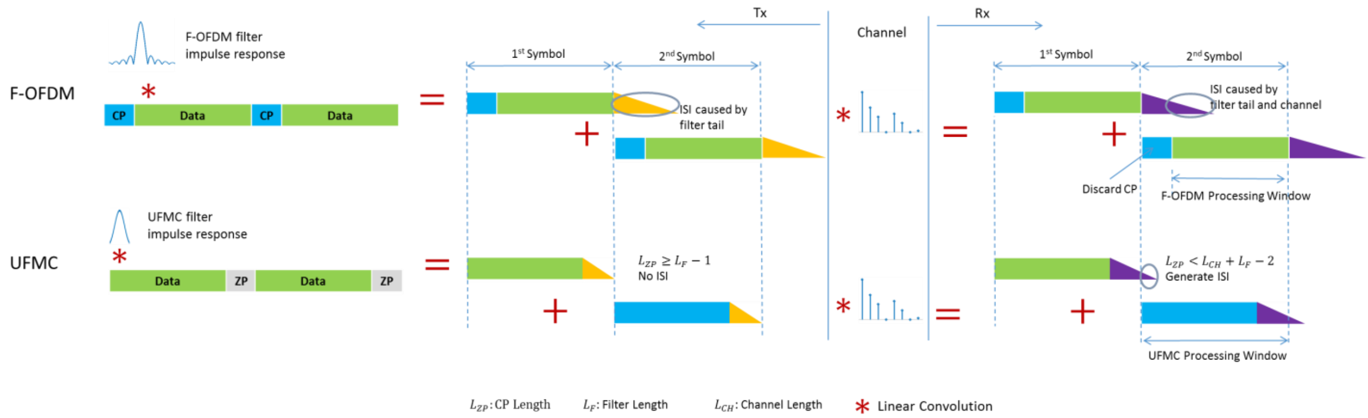

Fig. 2 F-OFDM and UFMC systems implementations

The time domain implementations of both F-OFDM and UFMC are shown in Fig. 2, where only one subband and two consecutive symbols are considered for demonstration purpose. Essentially, the UFMC is a ZP based multi-carrier system and the F-OFDM is the CP based one. The UFMC symbols do not overlap at the transmitter. However, this does not mean that UFMC is an ISI free system since the adjacent symbols will overlap after passing through a multipath channel as shown in Fig. 2. In F-OFDM systems, longer filter is used and filter tails extend to adjacent symbols [4]. Overlapping and ISI are unavoidable for a reasonable system overhead. At the receiver side, the UFMC and F-OFDM can use the standard ZP or CP based multicarrier system processing with a matched filter as an option.

B. Filter length, CP/ZP Length Selection and Impact on ISI/ICI

CP/ZP plays an important role in the OFDM system in terms of spectrum efficiency and performance. It can eliminate the ISI and allows low complexity interference-free one-tap channel equalization, if only the guard interval is equal to or longer than the channel length. This condition, however, is not sufficient for F-OFDM and UFMC systems.

State-of-the-art (SoTA) UFMC constrains the ZP length and the filter length to be equal to the channel length to trade-off the system overhead and performance [8] [11]. In such a case, the reserved ZP at the transmitter will be occupied by the filter tail completely. Though the filter ramp-up and ramp-down may mitigate the multipath channel effects to some degree, it cannot eliminate ISI completely.

In fact, the ZP length and the filter length can be de-coupled to optimize the system performance. For example, with a fixed overall system overhead, one can design a system with smaller filter length (thus, short filter tail) and leave some degree of freedom (i.e., zero at the end of the symbol) to mitigate the multipath channel dispersion. This might be especially useful for the symbol with pilot subcarriers for channel estimation.

With the short filter length and well time localization property, the UFMC system may suffer from more ISvcBI/ISubBI and performance loss due to inefficient power allocation in the multi-service system, which will be shown later in this article.

The CP length in F-OFDM is normally set to be the same as the channel length. However, the filter length can be as long as half symbol duration [4]. This design criterion provides very good frequency localization in the F-OFDM system. Allowing adjacent symbols to overlap at the transmitter side might subject the F-OFDM system to ISI contamination. However, filter impulse response decays significantly. In addition, the CP absorbs most of the energy of the filter if the subband bandwidth is not extremely small [4]. However, F-OFDM may require longer CP in narrow band systems to mitigate the ISI. Fig. 3 (a) shows the ISI versus the normalized subband bandwidth for different CP lengths (L_{CP}) in the F-OFDM system in the ITU UMi channel. It can be seen that a larger subband bandwidth leads to a smaller ISI and an increase in the CP length can significantly reduce the interference level.

C. Waveform Filter Frequency Selectivity and Impact on Performance

Compared with OFDM systems, SFMC systems may suffer from filter frequency response selectivity among subcarriers. This side-effect causes power allocation imbalance and performance loss if all subcarriers carry equally important information. This effect may be especially detrimental for the UFMC system [3]. In particular, the passband bandwidth of subband filter (e.g., Chebyshev filter) cannot be dynamically changed over a large range due to the short filter length, resulting in limited flexibility in the UFMC system design.

Fig. 3 (b) shows the relationship of the filter length with the subband bandwidth for different filter peak to bottom gain ratio (PBGR) (i.e., the ratio of the maximum and minimum filter gain among all subcarriers within one subband) [3]. Note that RBGR = 0 dB means there is no frequency selectivity among the subbands. In this case, UFMC degrades to an OFDM system. Fig. 3 (b) shows that longer filter results in a larger PBGR and greater performance loss. In addition, narrower subband bandwidth results in a smaller PBGR and, thus, better performance. Fig. 3 (b) can be used in multiple ways for the design of UFMC based 5G systems. For example, we can select appropriate subband bandwidth to achieve a certain PBGR for a given total number of subcarriers and filter length. Similarly, for given filter length and subband bandwidth, it is easy to calculate corresponding PBGR, based upon which the performance loss can be evaluated.

The frequency selectivity may also affect the channel estimation algorithms and optimal pilot pattern design. It is preferable to assign pilots at the subcarriers with the largest filter gain (i.e., in the middle of one subband). In addition, traditional channel estimation algorithm such as polynomial interpolation is no longer suitable for the SFMC system.

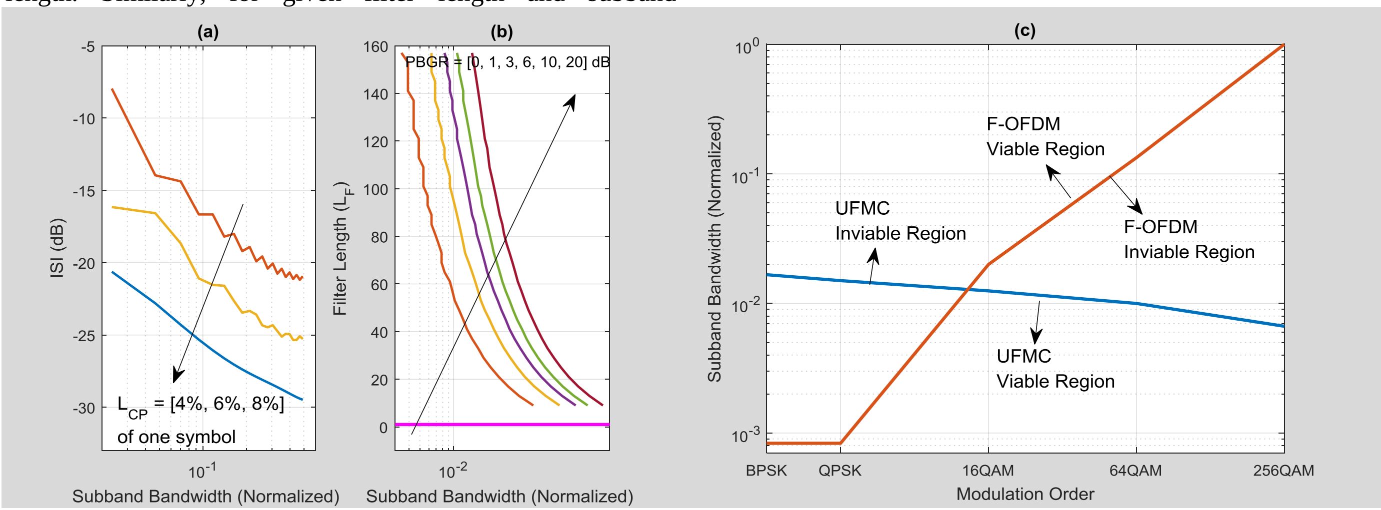

Fig. 3 F-OFDM and UFMC performance in terms of subband bandwidth: (a) ISI versus subband bandwidth with different CP length for F-OFDM; (b) Filter length versus subband bandwidth with different PBGR for UFMC; (c) Viable (subband bandwidth) region of F-OFDM and UFMC

D. *Waveforms' Viable Subband Bandwidth Regions*

According to the earlier discussion, F-OFDM system is subband bandwidth low-bounded system and UFMC is subband bandwidth high-bounded system. Fig. 3 (c) shows simulation results illustrating the bounds and the viable subband bandwidth region of the two waveforms in the ITU UMi channel for different modulation levels in order to reach 10^{-3} or lower un-coded bit error rate (BER). It can be seen that when modulation levels are low, both waveforms have larger viable ranges. As the modulation level increase, the viable subband bandwidth tends to reduce. With given ZP/CP length and system bandwidth, Fig. 3 (c) implies that small subband bandwidth is more suitable region for UFMC since it has smaller filter gain frequency selectivity and, thus, smaller overall performance loss. The F-OFDM, on the other hand, prefers to use larger subband bandwidth to keep the system from the ISI contamination.

The viable region directly relates to the design flexibility and complexity. Small subband bandwidth may bring more degrees of freedom in the design, e.g., narrowband mMTC services. For this reason, the F-OFDM system may have limited applications. For example, F-OFDM can only support a single service with 256QAM to achieve the target BER; whereas up to 100 different subbands/services can be supported in UFMC. However, too small subband bandwidth leads to higher computational complexity. In addition, in the eMBB/ URLLC scenario, relatively larger subband may be granted to one user. Thus, multiple subbands for one user may lead to unnecessary complexity. In such a scenario, F-OFDM is a preferred choice.

IV. SR AND MR IMPLANTATION OF MULTI-SERVICE SYSTEMS

There are two implementations for the multi-service SFMC system: SR and MR. Compared with SR system, the MR system has significantly reduced computational complexity but may suffer loss in performance due to the ISubBI. The implementations and comparisons will be studied in the next with a conclusion on their prospective application scenarios.

A. *SR and MR Systems Orthogonality Analysis*

In the SR system, as shown in Fig. 4 (a and b), the orthogonality between the subcarriers in one service is ensured by taking the corresponding columns of the full-size inverse discrete Fourier transform (IDFT) modulation [14]. One of the important roles of subband filter is to reduce the ISvcBI among the services. Such a system may have very high computational complexity.

Alternatively, MR system reduces the system complexity by up- and down-sampling the signals. As shown in Fig. 4 (c and d), it uses low-dimension full-size IDFT (DFT size is the same as the number of subcarriers in one subband, e.g., 12) that spreads the signal into the whole baseband bandwidth. The following up-sampling operation squeezes the signal into $1/Q_i$ of the full bandwidth with $(Q_i - 1)$ image signals in adjacent bands. An anti-image subband filter is required to mitigate the image signals (i.e., ISubBI) [14]. Nevertheless, the residual image signal will create the ISubBI in the system due to non-ideal filters, which may degrade system performance in comparison with the SR.

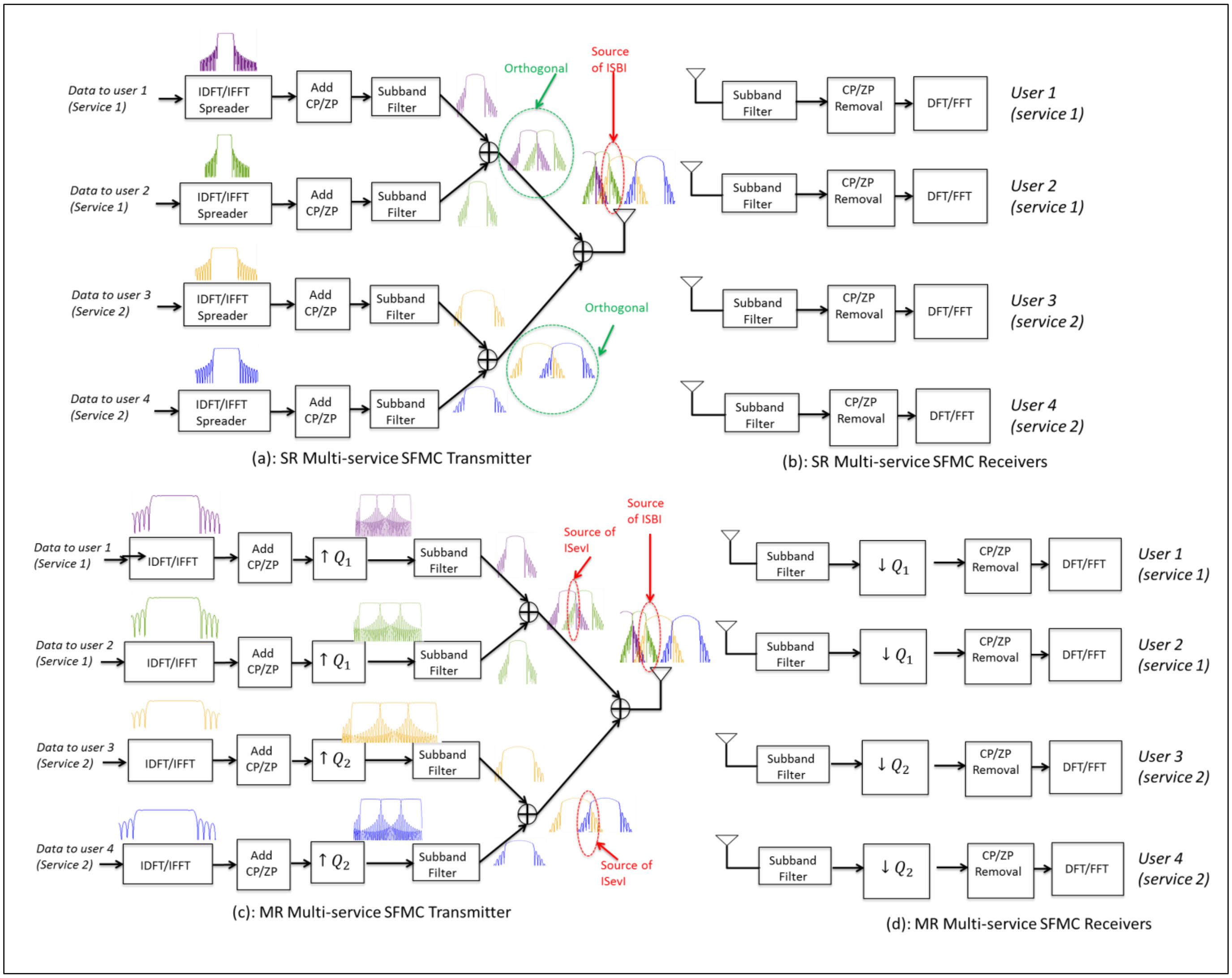

Fig. 4 Transmitter and receiver block diagram of SR and MR multi-service systems (For brevity, we consider 4 users in this diagram. User 1 and 2 belongs to the service 1, and user 3 and 4 belongs to service 2).

Note that the ISubBI is generated in both transmitter and receiver sides if both use the MR implementations. However, one can use the MR implementation at one side and SR at the other. For example, by using the computational capability advantage at the base station, we can implement the SR at base station and MR in the mobile station. In addition, we can build a hybrid system by using SR in some subbands with high communication QoS requirements (e.g., eMBB) and MR implementations in others which require low computational complexity (e.g., mMTC).

B. Computational Complexity of the SR and MR Systems

The transmitter computational complexity in terms of the real multiplication of the MR and SR systems for both waveforms is shown in Fig. 5 (the detailed calculation methods can be found in [3] and [14]). Note that the complexity is based on one service and it is normalized by the complexity of the OFDM system. The subband bandwidth for UFMC is 16 subcarriers, and there is only one subband in F-OFDM (i.e., it is service based implementation as shown in Fig. 1 (a-3)).

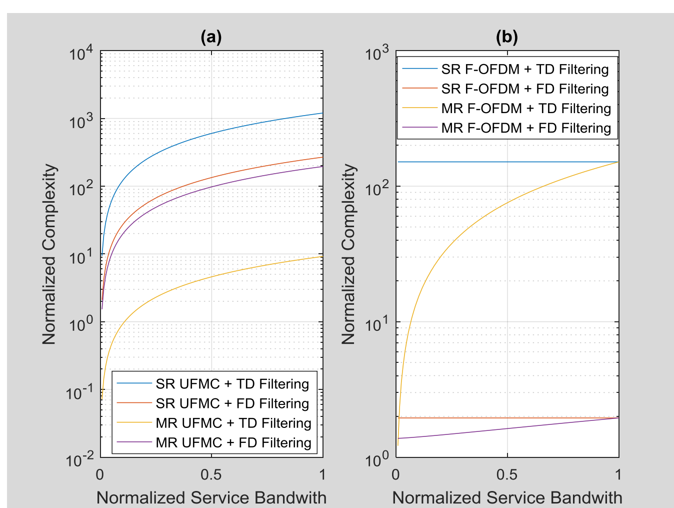

Fig. 5 UFMC and F-OFDM based multi-service system computational complexity (Normalized by OFDM system)

The subband filtering can be implemented either by following the traditional linear convolution in time domain (TD), or by using FFT in frequency domain (FD). In MR, the TD subband filtering can take the computational complexity advantage of up-sampling operation since the data is sparse [14]. For the UFMC system, we can see that SR implementation complexity is significantly (up to 1000 times) higher than OFDM system, while the MR system with TD filtering can achieve comparable complexity as the OFDM system. On the other hand, the complexity reduction in F-OFDM by using MR implementation is less significant in large service band region since there is only one subband in the service. The FD filtering is essential for both SR and MR implementations due to the long filter setup in F-OFDM system.

V. ISvcBI and ISubBI Cancellation Algorithms for Multi-service Systems

Using guard band between service bands/subbands can mitigate the ISvcBI/ISubBI, however, at the expense of spectrum efficiency reduction. In the following, we propose the baseband signal processing method to cancel ISvcBI/ISubBI either at transmitter or receiver side.

A. *ISvcBI Cancelation Algorithms*

Usually, the information carried in two service bands belong to two different users. Thus, it is difficult to cancel the interference at the user side. In addition, the BS has much higher computational capability to deal with the interference. Therefore, pre-processing the transmit signal at the transmitter in downlink or joint detection in uplink at the receiver can be proposed to cancel this type of interference.

Note that non-adjacent service bands do not generate significant ISvcBI and affect the performance. For example, in Fig. 1 (a-1), the 4-th and 5-th subbands located at the edge of the first and the second service may generate and suffer from severe ISvcBI. However, the 3-rd subband does not generate ISvcBI in the 4-th suband, which acts as a buffer zone attenuating the interference from subband 3 to subband 5. In addition, for the 4-th and 5-th subbands, due to the fast attenuation of the filter response in the stopband, only some subcarriers (e.g., last subcarrier of the 4-th subband and 1-st subcarrier of the 5-th subband in Fig. 1 (a-1)) at the edge of service bands may suffer from severe interference.

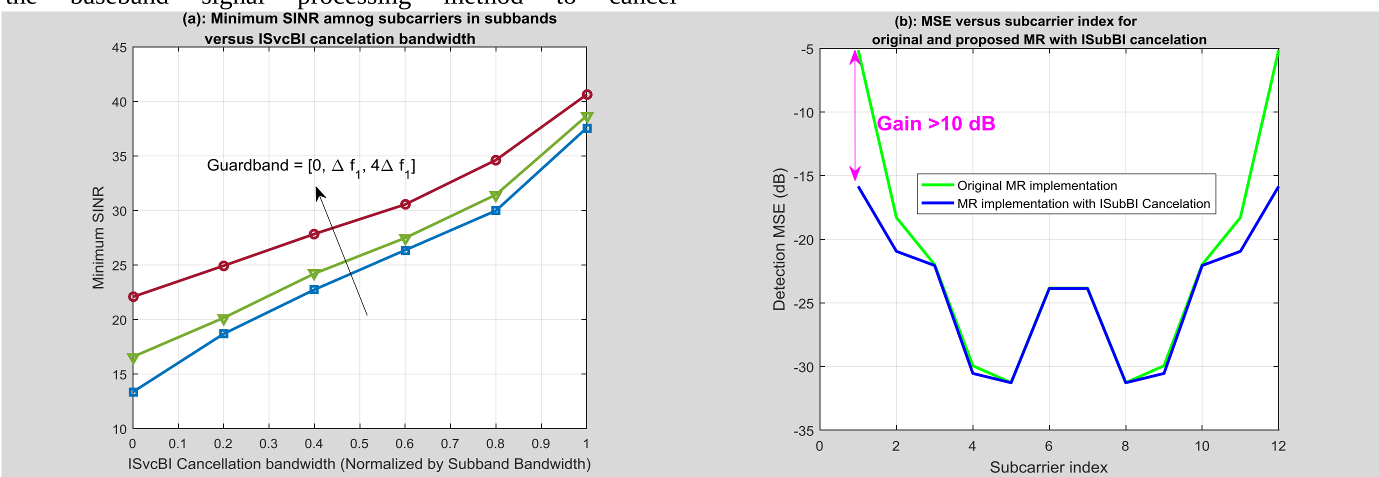

Fig. 6 Multi-service system performance with ISvcBI and ISubBI cancelation (each subband contains 12 subcarriers)

The optimal interference cancelation solution should be channel dependent. Fortunately, the considered bandwidth containated by ISvcBI are adjacent to each other and the interference level decrease exponentially in the subcarriers away from the edge of service band. Therefore, the channel response for all subcarriers, considred for ISvcBI cancelation, is approximately the same, resulting in a simplfied algorithm that does not depend on the channel [3]. Therefore, the solution can be calculated offline in advance to save the computational complexity. For the detailed ISvcBI cancelation algorithms, please refer to [3] for details.

The minimum SINR (worst-case) among the subcarriers in one subband (i.e., the edge subcarrier in the edge subband of one service band) versus the processing bandwidth (normalized by the subband bandwidth) is shown in Fig. 6 (a) for different values of guard band. The results are based on UFMC and we set the input SNR = 50 dB to make the system interference limited. The two considered subbands' subcarrier spacing has the relationship $\Delta f_1 = 2\Delta f_2$ and each subband has 12 subcarriers. Note that processing bandwidth being zero means no ISvcBI cancelation algorithm is used in the system. Fig. 6 (a) shows that larger GB leads to better output SINR. With the ISvcBI cancelation algorithm, the performance can be significantly improved.

B. *ISubBI Cancelation Algorithms*

Similar to the ISvcBI, non-adjacent subbands do not generate significant ISubBI and affect the performance. Therefore, we only consider subbands adjacent to each other in the frequency band. In addition, we can use low complexity channel independent ISubBI cancelation algorithm [14]. Fig. 6 (b) shows the proposed ISubBI cancelation algorithm for UFMC performed at the transmitter by precoding the transmit signals, where only two subcarriers at the edge are considered for the ISubBI cancelation as an example. One can see from the figure that the system performance after interference cancelation shows significant gain compared with the one without interference cancelation.

VI. Conclusions and Future Works

A framework for multi-service system is established based on subband filtered multicarrier (SFMC) modulation. The subband filtering implementations of the multi-service system have been discussed. The waveforms design criteria, orthogonality and fundamental limitation are studied with the conclusion that filtered orthogonal frequency division multiplexing (F-OFDM) may favor user or service based subband filtering for enhanced mobile broadband (eMBB) / ultra-reliable and low latency communications (URLLC). Universal filtered multicarrier (UFMC) is suitable for physical resource block (PRB) based subband filtering and the massive machine type communications (mMTC). We consider both single-rate (SR) and multi-rate (MR) signal processing with detailed analysis of inter-service-band-interference (ISvcBI) and inter-subband-interference (ISubBI). The proposed low complexity ISvcBI and ISubBI cancelation algorithm can significantly improve the system performance with limited guard band between subbands.

The future work on multi-service system includes, but is not limited to, the following topics: 1) design of new optimal channel estimation and equalization algorithms for the multi-service system by taking the waveform filter frequency selectivity into account; 2) low complexity interference cancelation algorithms for multi-input-multi-output (MIMO) cases should be investigated; 3) propose new synchronization algorithms in the presence of the non-orthogonal waveforms in multi-service systems; 4) mixed/hybrid MR and SR system, and/or mixed waveforms among service bands can be a research avenue to be explored. In addition, network slicing has been proposed recently in order to maximize the network utilization and reduce the operational expenditure [15]. The work presented in this paper shows how the network slicing can be underpinned in the physical layer in terms of signal multiplexing and isolation. Further technical challenges and potential applications of physical layer network slicing (PNS) could be a research topic in the future as well.

Acknowledgement

The authors would like to acknowledge the support of the University of Surrey 5GIC (http://www.surrey.ac.uk/5gic) members for this work.

References

[1] F. Schaich, B. Sayrac, M. Schubert, H. Lin, K. Pedersen, M. Shaat, G. Wunder, and A. Georgakopoulos, "FANTASTIC-5G: 5G-PPP Project on 5G air interface below 6 GHz," *European Conference on Network and Communications*, Jun. 2015.

[2] A. Osseiran *et al*., "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," in *IEEE Communications Magazine*, vol. 52, no. 5, pp. 26-35, May 2014.

[3] L. Zhang, *et al*., "Subband Filtered Multi-carrier Systems for Multi-service Wireless Communications," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 1893-1907, March 2017.

[4] X. Zhang, M. Jia, L. Chen, J. Ma, and J. Qiu, "Filtered-OFDM – enabler for flexible waveform in the 5th generation cellular networks," in *IEEE Globecom*, 2015, pp. 1–6.

[5] G. A. Shah, V. C. Gungor and O. B. Akan, "A Cross-Layer QoS-Aware Communication Framework in Cognitive Radio Sensor Networks for Smart Grid Applications," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1477-1485, Aug. 2013.

[6] S. H. R. Bukhari, M. H. Rehmani and S. Siraj, "A Survey of Channel Bonding for Wireless Networks and Guidelines of Channel Bonding for Futuristic Cognitive Radio Sensor Networks," in *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 924-948, 2016.

[7] F. Akhtar, M. H. Rehmani, and M. Reisslein, "White space: Definitional perspectives and their role in exploiting spectrum opportunities," Telecommunications Policy, 40(4), pp.319-331, 2016.

[8] G. Wunder *et al*., "5GNOW: non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 97–105, February 2014.

[9] RP-160671, "New SID proposal: Study on new radio access technology," 3GPP TSG RAN Metting~71, March 2016.

[10] H. Lin, "Flexible Configured OFDM for 5G Air Interface," in IEEE Access, vol. 3, no. , pp. 1861-1870, 2015.

[11] M. Fuhrwerk, J. Peissig and M. Schellmann, "On the design of an FBMC based AIR interface enabling channel adaptive pulse shaping per sub-band," European Signal Processing Conference, Nice, 2015, pp. 384-388.

[12] V. Vakilian, T. Wild, F. Schaich, S. Ten Brink, and J.-F. Frigon, "Universal-filtered multi-carrier technique for wireless systems beyond LTE," in *IEEE Globecom Workshops (GC Wkshps)*, 2013, pp. 223–228.

[13] A. Sahin, I. Guvenc, and H. Arslan. "A survey on multicarrier communications: Prototype filters, lattice structures, and implementation aspects," *IEEE Communications Surveys & Tutorials*, 16(3):1312–1338, March 2014.

[14] L. Zhang, A. Ijaz, P. Xiao, A. Quddus, and R. Tafazolli, "Single-rate and multi-rate multi-service systems for next generation and beyond communications," in *IEEE Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sep. 2016, pp. 1–6.

[15] K. Tsagkaris, *et al*., "Emerging management challenges for the 5G era: Multi-service provision through optimal end-to-end resource slicing in virtualized infrastructures problem statements and solution approaches," IEEE/IFIP Network Operations and Management Symposium, Istanbul, 2016, pp. 1297-1300.

Biographies

Lei Zhang received his Ph.D. in 2011 from the University of Sheffield, UK. He is currently a research fellow in Wireless Communications in the 5G Innovation Centre (5GIC), Institute of Communications (ICS), University of Surrey, UK. Before he joined ICS, he was a research engineer in Huawei technologies, China. His research interests include multi-antenna signal processing, multi-service air interface design, physical layer network slicing, cloud radio access networks, massive MIMO systems. He is holding 16 international patents.

Ayesha Ijaz received B.Eng in Electronic Engineering from University of Engineering & Technology, Taxila, Pakistan in 2006, M.Sc and PhD. in Mobile and Satellite Communications from University of Surrey, Guildford, UK in 2008 and 2011, respectively. She is currently a research fellow at the Institute for Communication Systems (ICS), home of 5G Innovation Centre (5GIC) at University of Surrey, UK. Her research interests include statistical signal processing and air-interface design for next generation wireless communication systems.

Pei Xiao received the B. Eng, MSc and PhD degree from Huazhong University of Science & Technology, Tampere

University of Technology, Chalmers University of Technology, respectively. Prior to joining the University of Surrey in 2011, he worked as a research fellow at Queen's University Belfast and had held positions at Nokia Networks in Finland. He is a Reader at University of Surrey and also the technical manager of 5G Innovation Centre (5GIC), leading and coordinating research activities in all the work areas in 5GIC (http://www.surrey.ac.uk/5gic/research). Dr Xiao's research interests and expertise span a wide range of areas in communications theory and signal processing for wireless communications.

Rahim Tafazolli is a professor and the Director of the Institute for Communication Systems (ICS) and 5G Innovation Centre (5GIC), the University of Surrey in the UK. He has published more than 500 research papers in refereed journals, international conferences and as invited speaker. He is the editor of two books on "Technologies for Wireless Future" published by Wiley's Vol.1 in 2004 and Vol.2 2006. He was appointed as Fellow of WWRF (Wireless World Research Forum) in April 2011, in recognition of his personal contribution to the wireless world. As well as heading one of Europe's leading research groups.